Modification of growing-season surface temperature records in the northern Great Plains due to land-use transformation: Verification of modelling results and implication for global climate change

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Modification of growing-season surface temperature records in the northern Great Plains due to land-use transformation: Verification of modelling results and implication for global climate change

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Abstract
Land-use and land-cover change can modify near-surface atmospheric condition. Mesoscale modelling studies have shown that modification in land use affects near-surface soil moisture storage and energy balance. Such a study in the Great Plains showed that changes in land use from natural grass to irrigated agriculture enhanced soil water storage in the root zone and increased latent energy flux. This increase in latent energy flux would correspond to a decrease in sensible heat flux and, therefore, modify

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near-surface temperature records. To verify this deduction, we have investigated the changes in the historical near-surface temperature records in Nebraska, USA. We have analyzed the long-term mean monthly maximum, minimum, and monthly mean air temperature data from five irrigated and five non-irrigated sites. The cooperative weather observation (coop) network is the source of the data. We have found that there is a clear trend in decreasing mean maximum and average temperature data for irrigated sites. For example, York, NE, reports that the mean maximum growing season temperature is decreasing at the rate −0.01 °C year^{-1}. The results from non-irrigated sites indicated an increasing trend for the same parameters. The data from Halsey, NE, indicate a +0.01 °C year^{-1} increase in this century. In addition, we have conducted similar analyses of temperature data for the National Climatic Data Center's Historical Climatic Network data set for the same locations. The results are similar to that obtained with the coop data set. Further investigation of dew-point temperature records for irrigated and non-irrigated sites also show an increasing and decreasing trend respectively. Therefore, we conclude that the land-use change in the Great Plains has modified near-surface temperature records.

Keywords: land-use change, temperature modification, climate change, the Great Plains

1. Introduction

The North American Great Plains has experienced a rapid overturning of natural grasslands to agricultural land use over the last century. In some areas, more than 80% of the land use has changed from dry land to irrigated agriculture (total change 2300%, from the 1950s to the 1990s) during the second half of the 20th century (Figure 1). We speculate that these changes have modified near-surface atmospheric temperatures. Availability of more water for evapotranspiration due to irrigated land use leads to greater partitioning of energy into latent heat. Thus, less energy is available as sensible heat. Near-surface warming of air is largely dependent on sensible energy availability. Hence, other factors being equal, a greater partitioning of energy into latent heat would lead to long-term cooling of daily near-surface air temperature.

To identify changes in land-surface–atmospheric interactions and near-surface hydrologic conditions, a soil moisture–energy balance model is applied (Robinson and Hubbard, 1990; Mahmood and Hubbard, 2002; Mahmood and Hubbard, 2003, in press) for three land uses (natural grass, rain-fed maize, and irrigated maize) at three locations in Nebraska, including Mead, Clay Center, and McCook. These locations represent the east (wet) to west (dry) hydroclimatic gradient of the Great

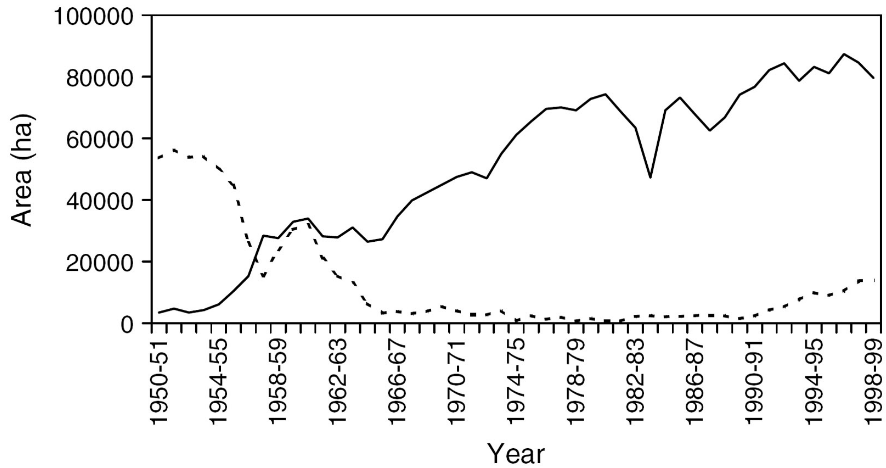

Figure 1. Irrigated (unbroken line) and rainfed maize land use in York County, Nebraska (Source: Mahmood and Hubbard, 2002).

Plains. We have found from the model applications that land-use change has modified evapotranspiration (ET) and near-surface soil moisture amount (and thus energy balance) in the northern Great Plains (NGP). For example, at McCook, NE, ET for irrigated maize is nearly 36% higher than for natural grass (Figure 2(a)). Significant change in energy partitioning and soil moisture is also noted due to these changes (Mahmood *et al*., 2001) (Figure 2(b) and (c)). As noted above, it is expected that a change in energy partitioning of this magnitude should have an imprint on surface temperature records.

The primary goal of this study is to examine the impacts of the land-use change on the near-surface temperature record of the NGP during the growing season. In this paper, we will focus mostly on mean monthly maximum, minimum, and mean temperatures. Long-term changes in diurnal range are also inspected. It is expected that, due to land-use change, the most notable modification of energy balance occurs during the growing season (May through to September). Hence, our analysis of air temperature data primarily focuses on this time period. Recently, Adegoke *et al*. (2003) and Mahmood *et al*. (2002) analyzed the same temperature data in the context of a modelling study to investigate the land-use forcing on the near-surface energy balance at the meteorological time scale. The present study provides a further detailed evaluation of the land-use forcing on long-term temperature records.

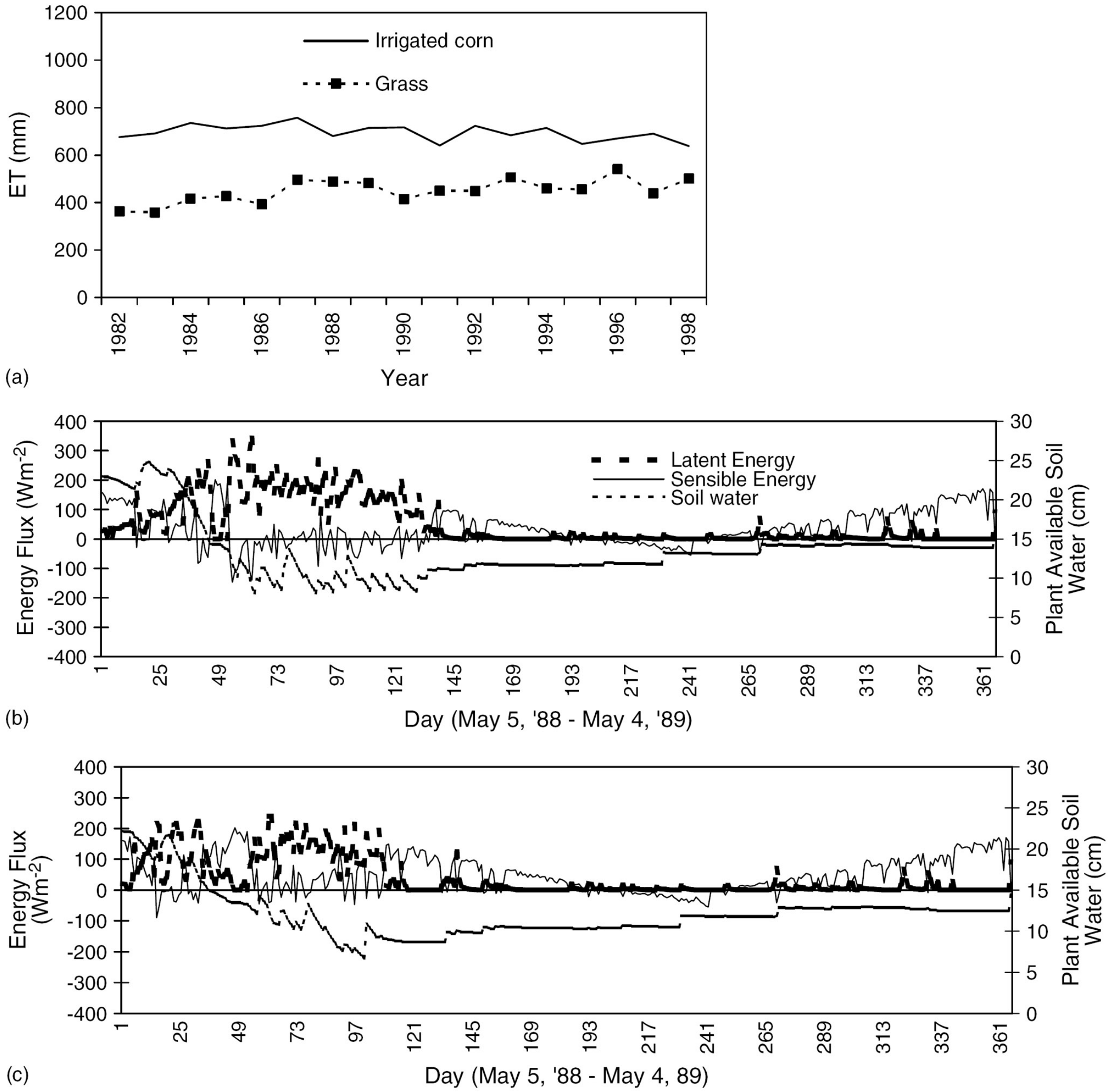

Figure 2. (a) Annual total evapotranspiration at McCook, NE, for two land uses. Energy partitioning and soil moisture under: (b) irrigated maize and (c) grass land use at McCook, NE (1988–89). Simulation starts on 5 May (day 1) and ends on 4 May (day 365).

Pielke *et al*. (2002) suggested that changes in vegetation cover modify energy partitioning and, thus, that a new approach should be adopted to quantify the impacts of these changes on the local, regional, and global climate system. They also noted that land-use changes in remote places may have opposing impacts on local and regional climate, and hence that spatial averaging may mask the true conditions (Pielke *et al*., 2002) and may also result in erroneous quantification of climate systems.

Model simulations indicate that latent and sensible heat flux may change locally and regionally, without changing global average (Chase *et al*., 2000). Additionally, Chase *et al*. (2000) showed that the tropical land-use change may have a forcing similar to El Niño. They noted that land-use modification in one region may result in changes in surface fluxes in another region through nonlinear atmospheric feedbacks (Chase *et al*., 2000). Therefore, locally and regionally, impacts of land-use change may be direct (through modification of surface energy budgets); however, globally, it is more complex. Pielke *et al*. (2002) noted that land-use change tends to occur in one direction in contrast to the changes back and forth from one state to another associated with El Niño and La Niña. Thus, impacts of land-use change may not be as obvious. In addition, Niyogi *et al*. (2002) noted that, for similar land-use change in different regions, forcings on the climate system may differ due to other factors in the different geographical regions. Pielke *et al*. (2002) suggested that energy partitioning directly influences near-surface temperature and should be considered as climate forcing. Moreover, changes in global mean temperature may contain vital information and the signature of local and regional land-use changes (Pielke *et al*., 2002). The Intergovernmental Panel for Climate Change (IPCC) suggest that there is 'discernible' evidence of climate change due to human activity (Houghton, *et al*., 1995). Pielke (2002) correctly concluded that if we fail to include land-use changes and their impacts on the climate system, then any agreement between general circulation model (GCM) simulations and observations may be due to the 'wrong reasons'. He further suggests that we need to test the hypotheses that landscape directly and indirectly influences the Earth's radiation budget and that land-use change affects local, regional and global climate at all time scales and that forcing due to land-use change is as important as radiative forcing of doubled carbon dioxide. In our opinion, it would be beneficial to study further the temperature changes due to local- and regional-scale land use prior to testing these hypotheses.

2. Background

Durre *et al*. (2000) conducted a study on the summertime extreme daily maximum temperatures and antecedent soil moisture. They found that, in the central USA, a drier soil condition is associated with higher air temperatures. It is noted that, during summer, daily maximum temperature east of the Rocky Mountains shifts towards higher temperature under a dry soil condition (Durre *et al*., 2000). They also report that, on a time scale shorter than 1 month, the frequency of record and near-record high temperatures is sensitive to soil moisture condition. Walsh *et al*. (1985), Chang and Wallace (1987), and Williams (1992) showed in their studies that higher soil moisture content reduces mean monthly temperatures for the current and following months. Georgakakos *et al*. (1995) found that there can be 5–10 days' lag in correlation between soil moisture and daily maximum temperature. Geographical location played an important role in these variations of lag. The important point is that soil moisture is a modulator of daily maximum temperatures. Physically, this is because energy partitioning is dependent upon surface moistness. Other factors being equal, increased soil moisture results in a greater latent energy flux.

Hogg *et al*. (2000) investigated the forcing of deciduous forest phenology on seasonal climatic pattern in the western Canadian interior. Their study shows 2 °C cooling of summertime temperature from the best-fit sinusoidal function. It is found that latent heat flux increases when leaves start to appear and dominates the energy partitioning during summer (Hogg *et al*., 2000). Physically, irrigated land use would enhance the rate of latent heat flux, and thus would depress daily maximum temperatures. We will show that the results of the present study are in agreement with the physical reasoning shown in Mahmood and Hubbard (2002), Durre and Wallace (2001), and Bonan (1999).

In the past, Segal *et al*. (1989) reported that there was a 10 K temperature difference between irrigated and adjoining dry land use in eastern Colorado. This observation was recorded using satellite surface-infrared temperature data. Surface and aircraft-based measurements also demonstrate significant lower boundary temperature and moisture content differences between dry land and irrigated land uses. Idso *et al*. (1981) showed that the surface temperature for irrigated alfalfa may be 12 K cooler than the surface temperature of a dry alfalfa field with severe water stress. Bounoua *et al*. (2000) conducted a model-based study and used global normalized difference vegetation index data from 1982 to 1990 to create maximum and minimum vegetation scenarios. They found a 1.8 K cooling during the growing season in the northern latitudes and attributed this cooling to a greater amount of energy partitioned into latent heat (Bounoua *et al*., 2000). In addition, they report soil dryness changes this partitioning pattern. Again, this underscores that when more water is used by plants, as under irrigated conditions, the higher soil moisture content will lead to higher latent energy flux, which then reduces temperature. The effect may be largest on daily maximum temperature, because it occurs frequently in late afternoon during the time when plants are actively transpiring.

Zhao and Pitman (2002) investigated the impacts of land-cover change and increasing CO_2 on maximum temperature frequency and convective precipitation. They used the National Center for Atmosphere Research's CCM3 coupled with BATS and found a reduction in return value of maximum temperature in Europe (Zhao and Pitman, 2002). It is noted that replacement of deciduous forest with croplands over Europe reduced stomatal resistance, and this led to higher latent energy fluxes and lowering of temperatures (Zhao and Pitman, 2002). That study found that land-cover change resulted in a 2 °C reduction of maximum temperature in Europe. The level of CO_2 did not make any difference in this estimate. Hence, the impact of land-cover change on temperature was independent of atmospheric concentration of CO_2. Based on a modelling study, Bounoua *et al*. (2002) suggested that, in the temperate latitudes, land-use transformation to crop land would reduce summer temperature by up to 0.7 °C. They concluded that morphological and physiological changes in vegetation resulted in increased albedo and latent energy flux respectively, and this led to lowering of temperature.

Recently, Hoffman and Jackson (2000) demonstrated that changes from savannah to grass land influenced near-surface temperature. Fitzjarrald *et al*. (2001) reported that, in the eastern USA, mean temperature was reduced at the time of spring-season leaf emergence due to partitioning of most of the net radiation into latent energy. It is clear that, during the maximum vegetation growth, the daily maximum and mean temperatures become moderated due to modification in energy partitioning. Hence, again, it is expected that, with extensive irrigation, the near-surface irrigation thermal condition would be moderated further.

Fraderich *et al*. (1999) used 'desert world' and 'green planet' scenarios to determine forcings of vegetation on the general circulation of the atmosphere. They noted a significant increase in ET and subsequent reduction of near-surface temperature for the 'green world' scenario. Balling *et al*. (1998; Balling, 1988) investigated the impacts of land degradation on historical temperature records from southern Arizona and northern Mexico. The results show higher temperatures in northern Mexico compared with southern Arizona, due to land degradation. Daily temperature range (DTR) also increased on the Mexican side compared with Arizona. On the other hand, Collatz *et al*. (2000) suggested that a lowering of the DTR is possibly related to an increase in the Northern Hemispheric vegetation cover and resulted in enhanced latent energy flux. Recently, Chase *et al*. (1999) noted that there is a significant decrease in temperatures in northeast Colorado during 1981–95. They have attributed this change to large increases in irrigated agriculture and suggest that this change is localized (Chase *et al*., 1999).

It is clear from the above studies that changes in land use affect near-surface temperature. However, there is a lack of studies directly comparing impacts of dry land and irrigated land uses on near-surface temperature within a hydroclimatic domain. The present investigation addresses this concern. In addition, this study will verify, as discussed above, the results presented in Mahmood and Hubbard (2002).

3. Data and methods

The long-term mean monthly maximum, minimum, and average air temperature data from five irrigated and five non-irrigated sites were analyzed (Figure 3 and Table I). The reasons for selection of these stations are the length of the time series, the ability to represent areas of primarily dry land or irrigated land use, the completeness of record, and the stability of station location. The data were collected from the cooperative (coop) observation network. A number of these coop sites (see Table I) are part of the Historical Climate Network (HCN) as designated by the National Climatic Data Center (NCDC). Sites were given HCN designation only after passing screening and quality-control procedures as developed by the NCDC. Data from the HCN are also analyzed for these locations to determine whether the adjustments and screening of HCN data could impact the results of this study. Note that we have included data from Pawnee City for which only the HCN time series is available. The sites associated with irrigation are York, Osmond, Oakdale, Box Butte, and Alliance, and the sites associated with primarily dry land are Halsey, Chadron, Auburn, Valentine AP, and Pawnee City.

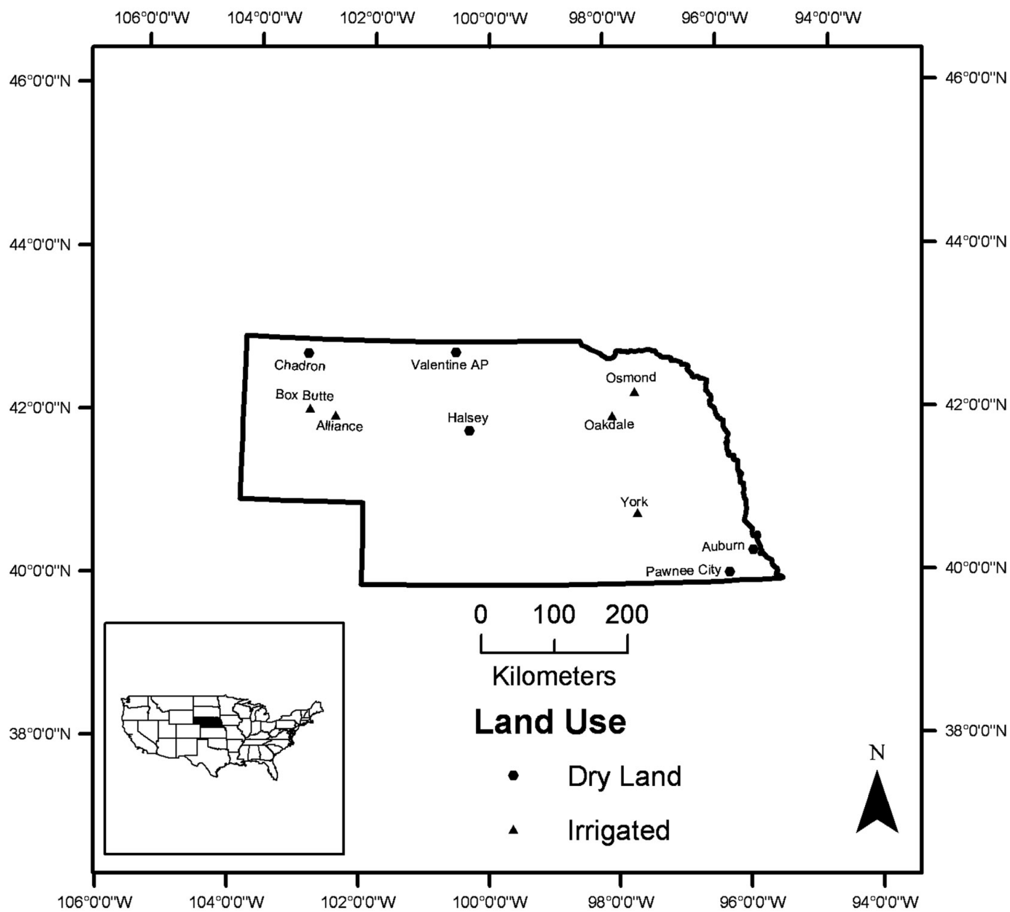

Figure 3. Location of meteorological stations in Nebraska and surrounding predominant land use.

Table I. List of cooperative and HCN station locations and associated land uses

Station name	County	Land use	Station status	Length of time series (Coop, HCN)
York	York	Irrigated	Cooperative, HCN	1921–2000, 1901–2000
Osmond	Pierce	Irrigated	Cooperative	1948–2000
Oakdale	Antelope	Irrigated	Cooperative, HCN	1893–2000, 1893–1999
Box Butte	Box Butte	Irrigated	Cooperative	1948–1981
Alliance	Box Butte	Irrigated	Cooperative, HCN	1894–2000, 1900–99
Halsey	Thomas	Dry land	Cooperative, HCN	1903–2000, 1903–2000
Chadron	Daws	Dry land	Cooperative	1948–2000
Auburn	Nemaha	Dry land	Cooperative, HCN	1893–2000, 1900–2000
Valentine AP	Cherry	Dry land	Cooperative	1948–2000
Pawnee City	Pawnee	Dry land	HCN	1903–99

This study analyzed dew-point temperature data from six locations. These sites include Beatrice, Central City, Champion, Clay Center, McCook, and North Platte. These locations represent dry land and irrigated land use. The longest time series for dew-point temperature data ranges from 1982 through to 2000. The lack of long time series for dew-point temperature has not been completely overcome, but it can partially be addressed with nearly 20 years of data from these locations of the NGP. The sites are part of the Automated Weather Data Network of the NGP. This network is maintained by the High Plains Regional Climate Center.

To determine the changes in the near-surface temperature, trend analyses were conducted for the mean growing season (May–September) maximum and minimum temperatures as well as the DTR. The growing season temperatures were calculated from monthly data. The trend analysis included a linear fit for the time series of each of the above variables. In addition, an 11 year running average was calculated to partially smooth the time series and variations associated with less than a decade in length. For selected stations, a separate analysis was conducted for the period 1921–50 and 1951–2000 to allow comparison of the period before and after rapid irrigation development. Rates of temperature change for each growing-season month and the long-term trends in dew point were also examined.

4. Results

First we present the results for the irrigated sites. We found a clear decreasing trend in growing-season mean temperature and mean maximum temperature for these locations. For example, at York, NE, both growing-season mean temperature and mean maximum temperature decrease at the rate of −0.01 °C year^{-1} (Figure 4(a) and (b)). Growing-season mean temperature data from other irrigated sites (Oakdale, Boxbutte, and Alliance) also show this decreasing trend; the exception is Osmond (Table II). However, analyses show all irrigated locations have a decreasing trend in mean maximum temperature. York and Oakdale are NCDC-designated HCN sites. The HCN data for these locations also show a decreasing trend for mean temperature and mean maximum temperature during the growing season. Growing-season mean minimum temperature data demonstrate an increasing trend for three irrigated locations: York, Osmond, and Oakdale. On the other hand, Boxbutte and

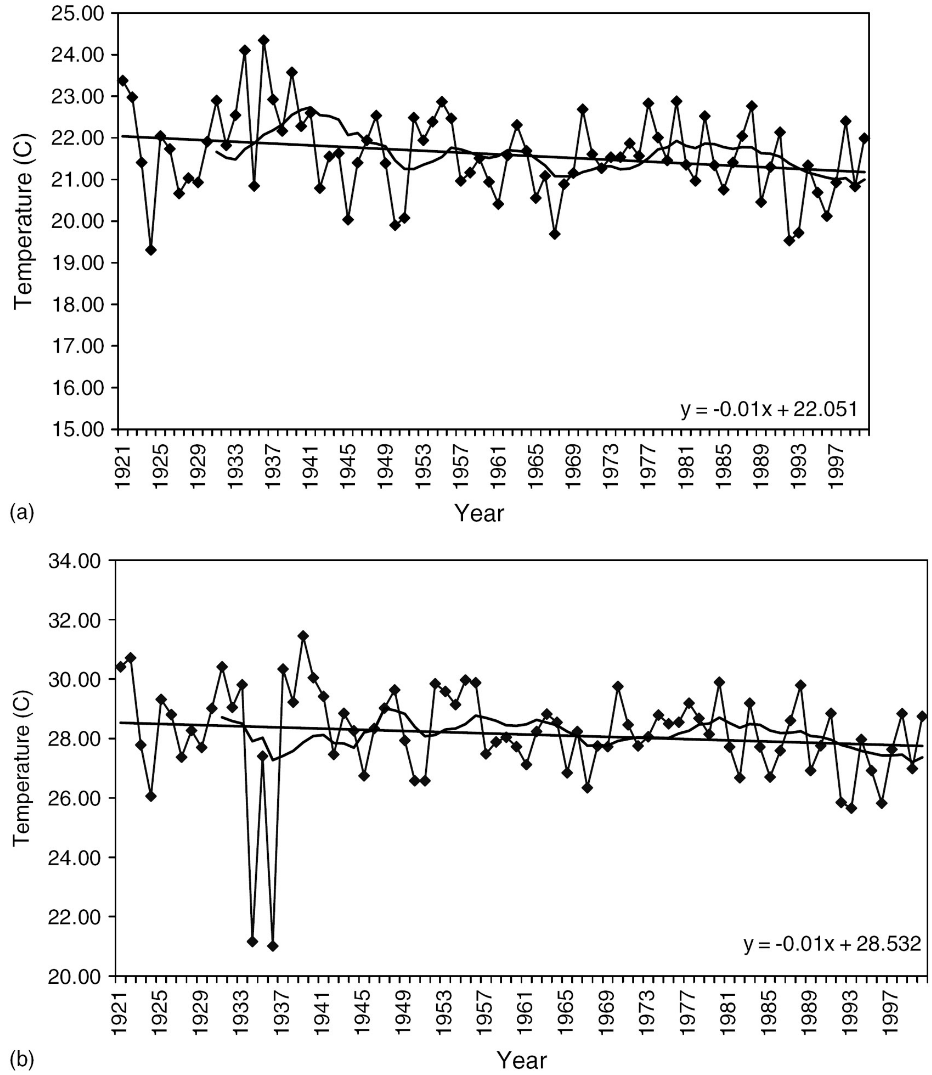

Figure 4. Growing-season (May–September) (a) mean and (b) mean maximum temperature trend at York, NE (predominantly an irrigated location). Nonlinear thick line shows the 11 year running average.

Alliance show a decreasing trend in growing-season mean minimum temperature. HCN data for York and Oakdale suggest an increasing trend in growing-season mean minimum temperature.

The analyses of coop data from non-irrigated sites indicate an increasing trend for the growing-season mean temperature for all locations except for Valentine AP. For example, at Halsey, NE, growing-season mean temperature and mean maximum temperature increased at the rate of +0.005 °C year^{-1} and +0.01 °C year^{-1} respectively (Figure 5(a) and (b)). The HCN data set for Pawnee City also record a +0.01 °C year^{-1}

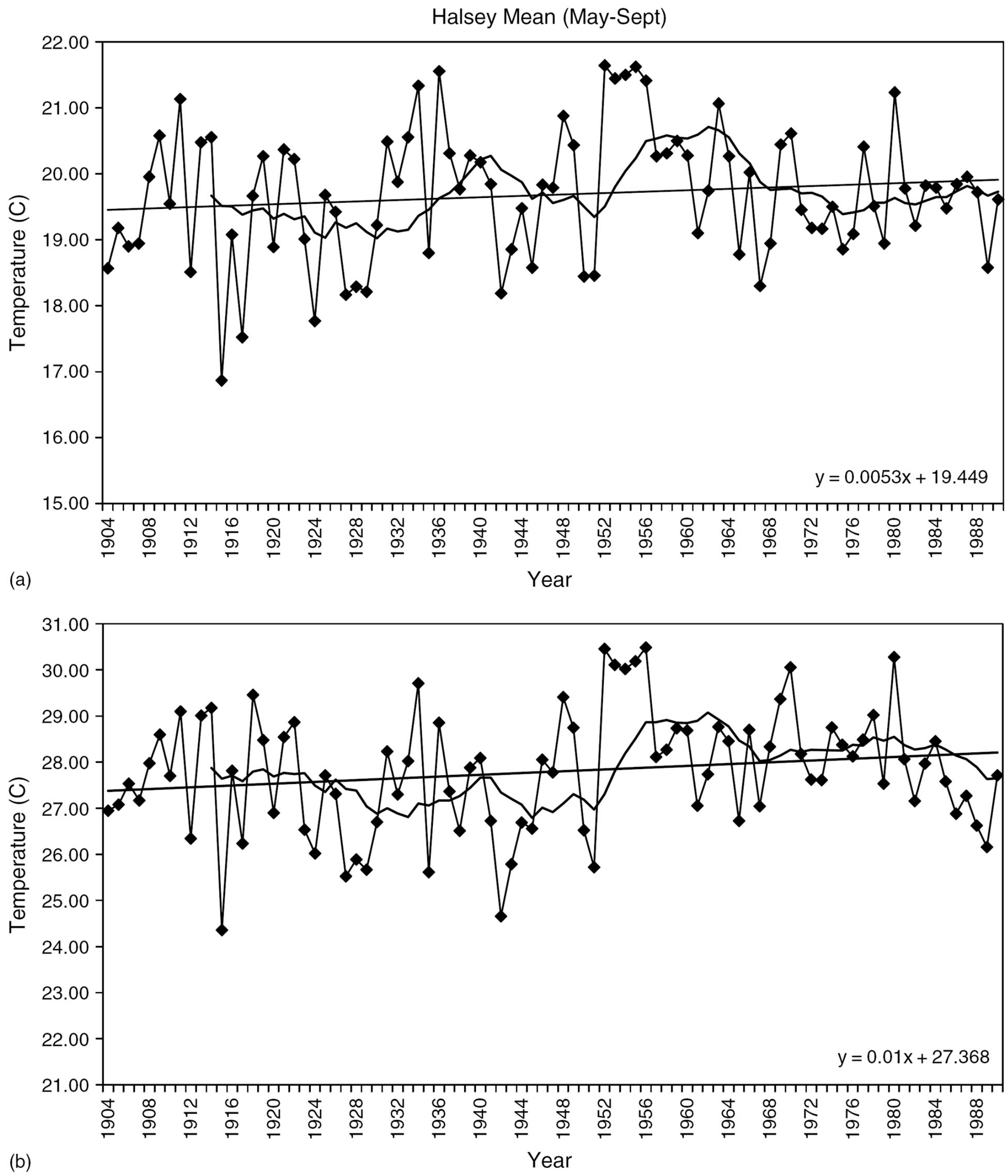

Figure 5. Growing-season (May–September) (a) mean and (b) mean maximum temperature trend at Halsey, NE (predominantly a non-irrigated location). Nonlinear thick line shows the 11 year running average.

increase in mean temperature for the growing season at a non-irrigated location. In the meantime, Chadron and Auburn suggest a decreasing trend in mean maximum growing-season temperature (Table II). However, the rate of increase in mean minimum growing-season temperature was high enough to offset the decreasing trend in maximum temperature to result in a positive trend in daily mean temperature. Although the

Table II. Rate of temperatures changes for 10 locations in Nebraska

Location	*Temperature (°C)*					
	Coop			*HCN*		
	Mean	*Mean max.*	*Mean min.*	*Mean*	*Mean max.*	*Mean min.*
York (1921–2000)	−0.0100	−0.0100	0.0015	−0.0005	−0.0101	0.0090
Osmond (1948–2000)	0.0006	−0.0100	0.0107			
Oakdale (1893–2000)	−0.0007	−0.0042	0.0030	−0.0008	−0.0045	0.0030
Boxbutte (1948–81)	−0.0037	−0.0061	−0.0020			
Alliance (1894–1950)	−0.0025	−0.0011	−0.0039			
Halsey (1904–50)	0.0053	0.0100	0.0009	−0.0014	−0.0016	−0.0010
Chadron (1948–2000)	0.0086	−0.0057	0.0230			
Auburn (1893–1950)	0.0038	−0.0002	0.0090	0.0058	−0.0028	0.0144
Valentine AP (1948–2000)	−0.0005	0.0151	−0.0160			
Pawnee City (1903–99)				0.0119	0.0092	0.0161

majority of nonirrigated locations show an increasing trend in growing-season temperature, the overall signal is not very clear.

Mean, mean maximum, and mean minimum growing-season temperatures were examined separately for pre- and post-1950s for three irrigated (York, Oakdale, and Alliance) and three non-irrigated locations (Halsey, Auburn, and Pawnee City). Both the coop and HCN data sets are used for this analysis. The six locations represent the longest time series among the stations included. The analysis of coop data shows that the pre-1950 mean growing-season temperature for York has decreased from 21.51 °C to 20.65 °C during the post-1950 period (Figure 6(a)). Alliance also recorded a decrease in mean growing-season temperature, from 18.58 °C to 18.38 °C respectively for the same time periods (Figure 6(b)). Growing-season mean maximum and mean minimum temperatures for York and Alliance indicate similar decreasing temperatures during the post-1950 period (Figure 6(a) and (b)). In addition, analysis of the HCN data set for York also agrees with the above results. As discussed above, the post-1950s period is associated with a spectacular change in land use with the introduction of irrigated agriculture. This led us to suggest that the land-use change is a major factor in the modification of these temperatures. Note that coop and HCN time-series-based calculated growing-season mean temperature and mean maximum temperature for post-1950 for Oakdale show a slight increase compared with pre-1950. This result is opposite to the overall long-term trend (1893–2000). During calculations of the pre- and post-1950 means, assessment of two shorter time series (1893–1950, 1951–2000) showed a masking of the overall long-term temperature trend in Oakdale.

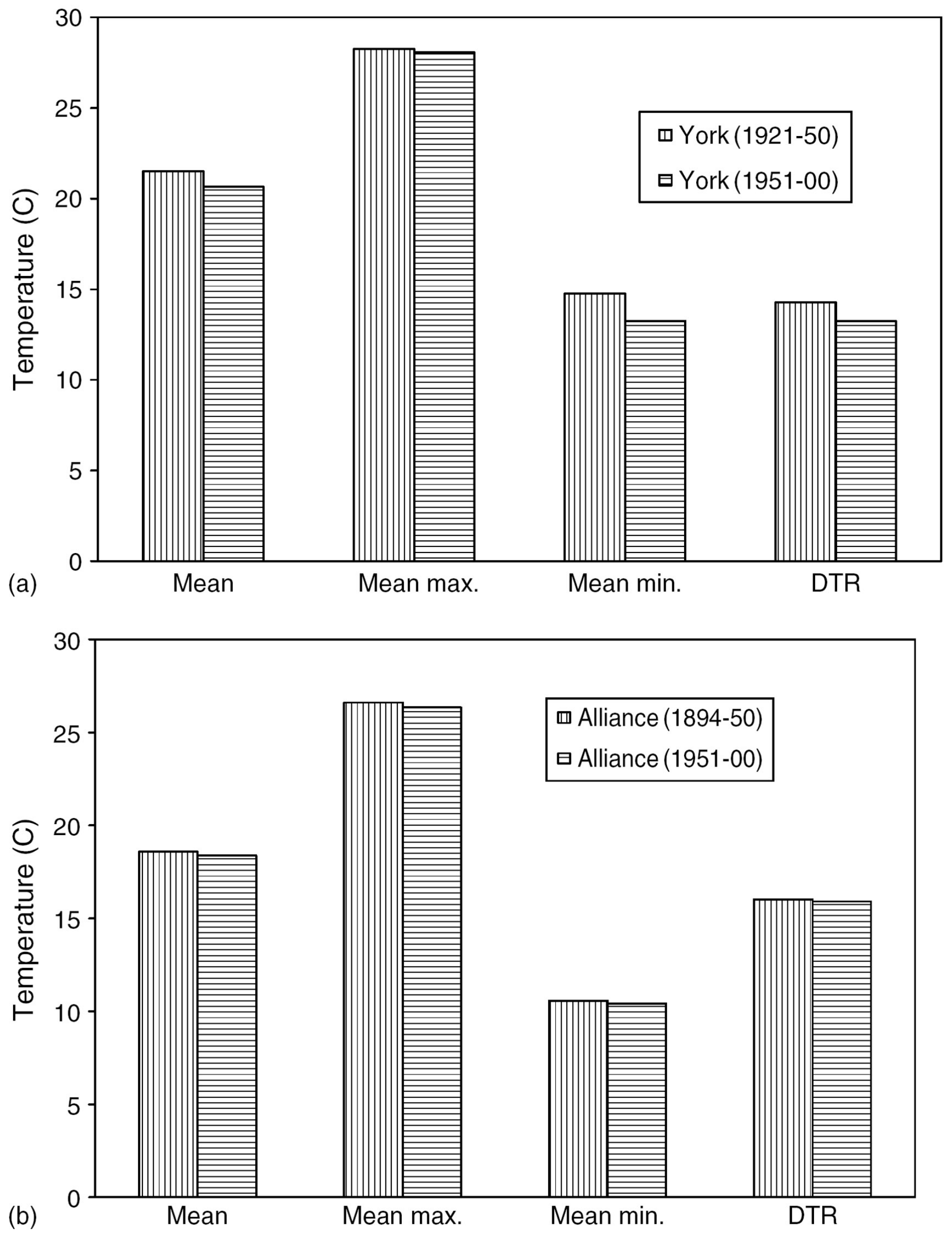

Figure 6. Growing-season (May–September) mean, mean maximum, and mean minimum temperature, and DTR for irrigated locations during pre- and post-1950s: (a) York, NE; (b) Alliance, NE. Confidence level for differences of growing-season mean and mean minimum temperatures and DTR is 99%.

In the meantime, the coop time series demonstrated that calculated mean minimum growing-season temperature for post-1950 has decreased compared with the pre-1950 period for York, Oakdale, and Alliance. The HCN time series for Oakdale is also in agreement with this result. In other words, the calculated mean minimum temperature change between pre- and post-1950 disagreed with long-term trends, as shown in Table II. For dry-land land use, both the HCN and coop data sets show that growing-season mean temperature for Halsey, Auburn, and Pawnee City has increased from the pre-1950 decades to post-1950 (Figure 7(a) and (b)). Both Halsey and Pawnee City recorded an increase

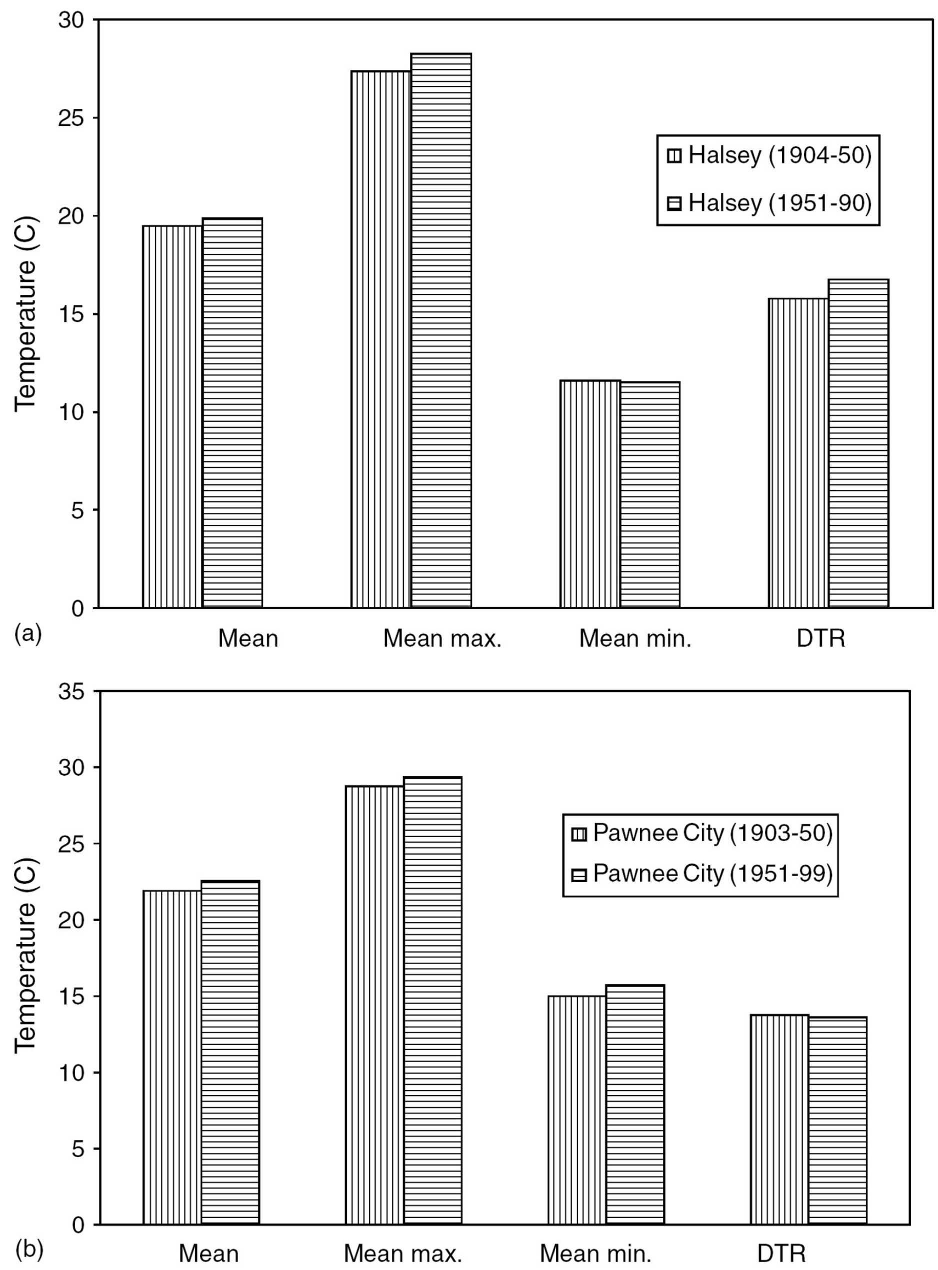

Figure 7. Growing-season (May–September) mean, mean maximum, and mean minimum temperature, and DTR for non-irrigated locations during pre- and post-1950s: (a) Halsey, NE; (b) Pawnee City, NE. Confidence level for differences of growing season mean and mean maximum temperatures and DTR is 99%.

in growing-season mean maximum temperature during post-1950 decades (Figure 7(a) and (b)). In addition, compared with the pre-1950s, Auburn and Pawnee City recorded an increase in growing-season mean maximum temperatures during post-1950 decades (Figure 7(b)).

In general, the potential maximum diurnal range of temperatures reduces when energy partitioning is dominated by latent heat flux. Thus, it is possible to speculate that, under irrigated land use, the diurnal temperature range (DTR) would decrease. For example, the coop and the HCN data sets for York (irrigated location) show a decreasing trend in DTR (Figure 8). Auburn and Pawnee City, representing dry land agricultural land use, also indicate a decreasing trend in diurnal range (Figure 9(a) and (b)) and thus agreed to the expected response under this land use. A comparison of pre- and post-1950 DTR suggests, in most cases, a decrease during the post-1950s for both dry land and irrigated land uses (Figures 6(a) and (b) and 7(a)). Global climate-change studies also indicate a decrease in diurnal range due to an increase in mean minimum temperature (e.g. Karl *et al*., 1993). Gallo *et al*. (1996) noted that DTR is sensitive to land-use change even within a 10 km radius of an observing location. They have found that, regardless of land-use type, DTR has decreased over the USA during the period 1950–96 (Gallo *et al*., 1999). Thus, our findings agree with the conclusion of Gallo *et al*. (1999).

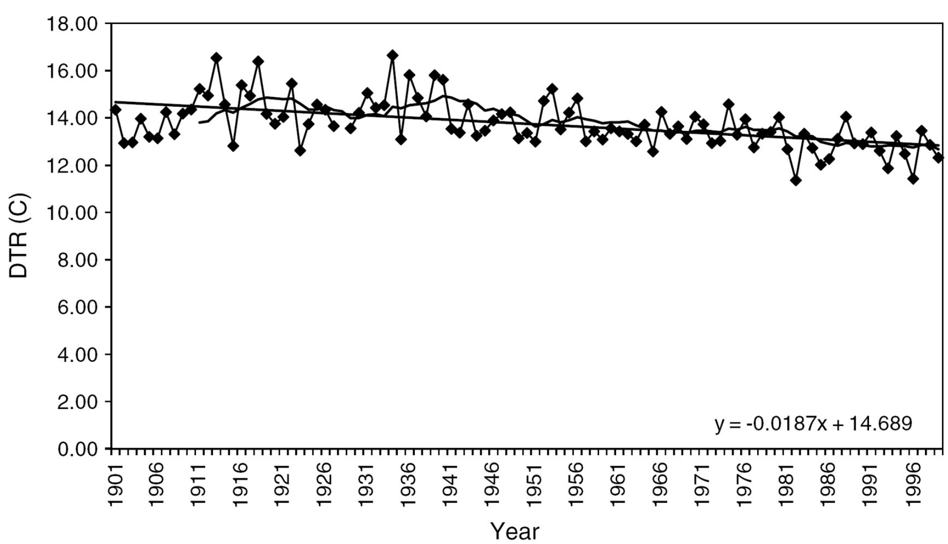

Figure 8. Trend in growing-season mean daily temperature range (DTR) for York, NE (an irrigated location). Nonlinear thick line shows the 11 year running average.

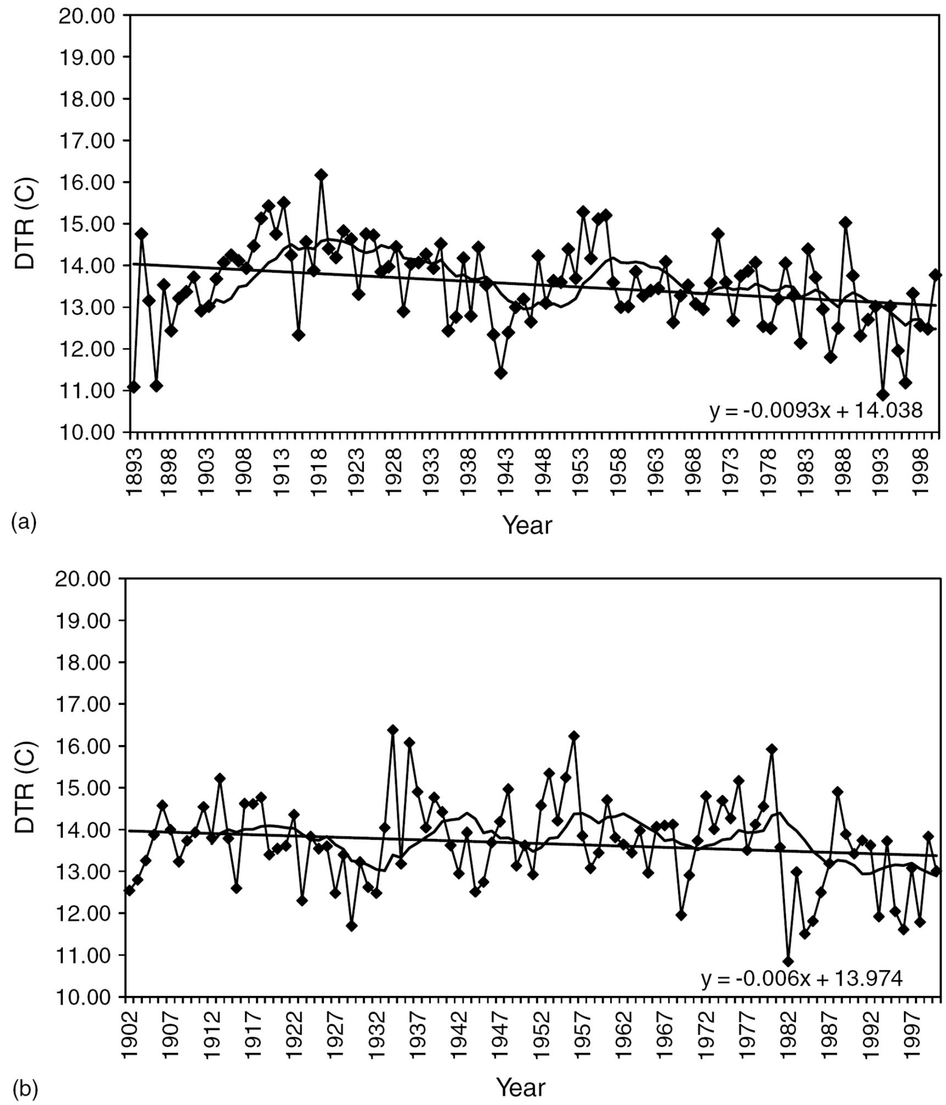

Figure 9. Trend in growing-season mean daily temperature range (DTR) for (a) Auburn, NE (a non-irrigated location) and (b) Pawnee City, NE (a non-irrigated location). Nonlinear thick line shows the 11 year running average.

Further diagnosis suggests that a rise in growing-season mean minimum temperature after 1950 plays a role in decrease in mean growing-season DTR in York, Auburn, and Pawnee City. Under irrigated conditions, a decreasing trend in DTR resulted largely from simultaneous lowering of growing-season mean maximum temperature and increase in mean minimum temperature. On the other hand, under dry-land land use, a greater increasing rate in mean minimum temperature, compared with mean maximum temperature, resulted in lowering of the DTR.

Thus, potentially, two different controlling factors are influencing the overall trend in DTR. Several model-based studies suggest that the surface ET can reduce daytime temperatures, although it has insignificant or no effect on night-time temperature (Cao *et al*., 1992; Mearns *et al*., 1995; Dai *et al*., 1999). We infer from this that our results for maximum temperature are directly and strongly linked to the change in land use. The results for minimum temperature likely are indicative of a complex land–atmosphere interaction system. Since the variations in the mean are due to changes in both the maximum and minimum, it follows that changes in the mean may not have a weaker connection to land use than changes in the maximum. We do call attention to the fact that both dry land and irrigated land uses show a rise in mean minimum temperature. Hence, it appears that land use did not make a unique difference in mean minimum temperature rise. We suggest a separate modelling study would be helpful in understanding the forcing factors and mechanisms.

The difference between the rate of mean maximum and mean minimum temperature change is also overwhelmingly, suggesting a negative trend for both irrigated and dry land uses (not shown). This negative trend is partly influenced by the positive trend in mean minimum growing-season temperature. Therefore, again, according to our results, the mean minimum growing-season temperature range is possibly, as indicated above, a function of mechanisms other than land use.

Rates of temperature change for irrigated land use for each of the growing-season months were calculated. For all irrigated locations, and for most of the individual months, there is a decreasing trend in mean maximum temperature. July and August show the greatest rate of decrease in mean maximum temperatures (Figure 10(a)). The mean temperature change for irrigated locations also shows a similar decreasing trend (Figure 10(b)). July and August are the most active period of plant growth, and they consume and transpire more water during this time. Farmers also supply a greater amount of irrigation during this period to fulfil plant water-demand. Hence, more water is also available for evaporation. Overall, the thermal condition during July and August is very warm, and this provides a suitable environment for ET at a greater rate. Thus, it is expected that the rate of reduction of mean maximum temperatures for irrigated locations would be greater during July and August.

We postulated that land-use change from dry land to irrigated agriculture would moderate extreme temperatures. Analysis of monthly data

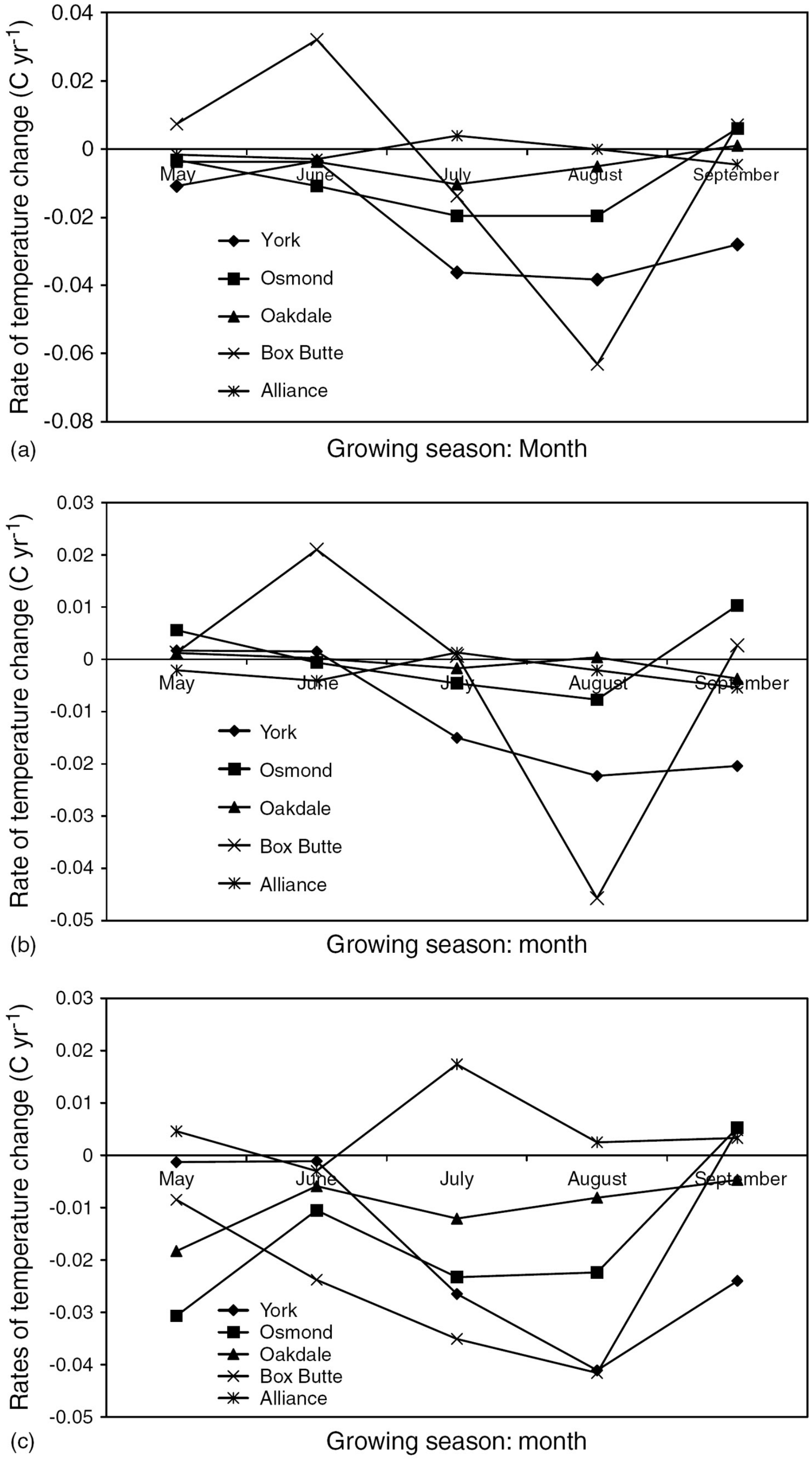

Figure 10. Rate of (a) monthly mean maximum, (b) monthly mean, and (c) monthly extremely high temperature change under irrigated land use.

shows that York, Osmond, Oakdale, and Box Butte recorded a decreasing trend in extremely high temperatures (Figure 10(c)). Temperatures of July and August show the greatest rate of decrease. As explained above, forcing of modified near-surface hydrology resulted in these decreasing rates of extreme temperature change.

In addition, we have conducted similar analyses of the HCN data set for the same locations. The results are similar to those obtained with the coop data set. It is speculated that the modification of land use would also modify near-surface atmospheric moisture status. Thus, analyses of dew-point temperature records for irrigated and non-irrigated sites are conducted. The results show an increasing trend for an irrigated environment. For example, at Clay Center and Central City, the dew-point temperature has increased at the rate of +0.04 °C year^{-1} and +0.14 °C year^{-1} respectively (Figure 11(a) and (b)). Therefore, it is clear that the

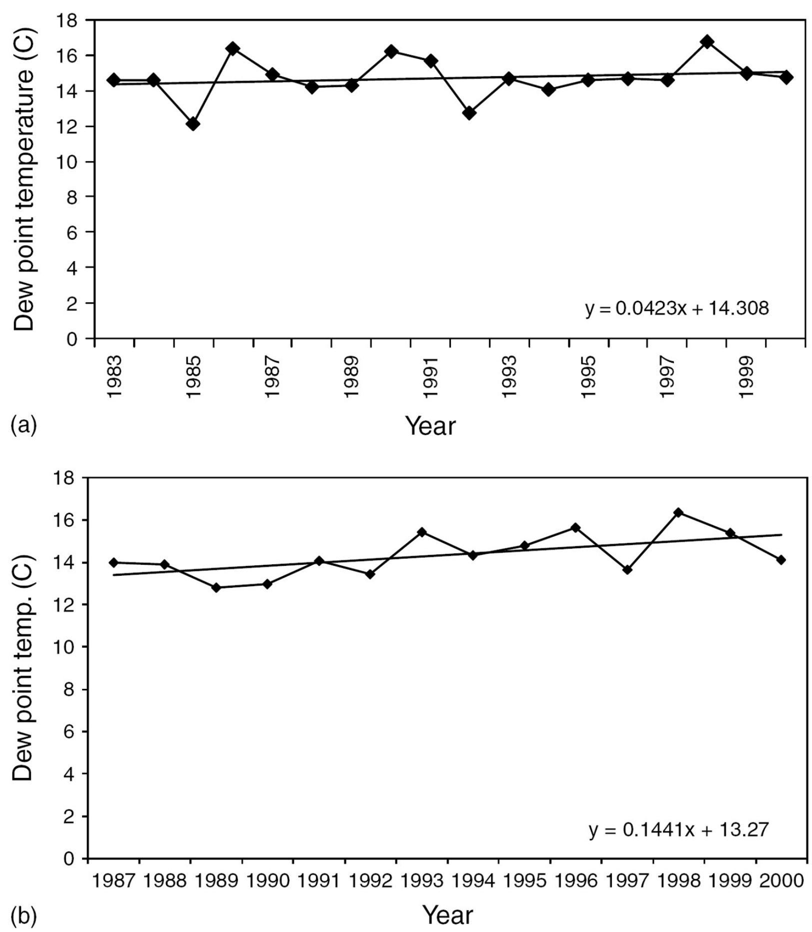

Figure 11. Dew-point temperature trend at (a) Clay Center (an irrigated location) and (b) Central City (an irrigated location).

land-use change in the Great Plains has modified near-surface moisture content, and hence surface temperature records, through repartitioning of energy between latent and sensible heat flux.

5. Discussion

A number of studies have been conducted in recent years to explain changes in DTR with the progression of seasons (e.g. Robinson *et al*., 1995; Leathers *et al*., 1998; Durre and Wallace, 2001). Summertime dipping of the DTR is related to establishment of the growing season (Durre and Wallace, 2001). Several studies by Schwartz (1992, 1996; Schwartz and Karl, 1996) have found an increase in atmospheric water vapor after first leaf appearance. They surmised that the increase in ET resulted in a higher atmospheric water vapor content, which led to a decrease in daytime warming and thus in DTR. This suggestion is similar to our earlier note; that a decrease in daytime mean maximum temperature and the DTR in irrigated locations is related to greater ET and a larger amount of energy partitioning to latent heat.

Leathers *et al*. (1998) and Durre and Wallace (2001; Figure 2) demonstrated a DTR minimum towards the end of the summer (July and August). This minimum is primarily connected to a high rate of ET during this period and resultant suppression of daily maximum temperature. The present study also reports a larger rate of decrease for daily mean maximum temperature during July and August (Figure 10(a) and (b)) over the irrigated locations. Again, as noted previously, higher water consumption and ET by plants during this period results in these augmented decreasing rates. Durre and Wallace (2001) discussed the increase in DTR as plants approach senescence. In our study, larger rates of decrease in monthly mean and monthly mean maximum temperatures in irrigated locations do not persist through the final months of the growing season because plants reach their maturity and the reduction in ET lessens the suppression of daily maximum temperatures. In this sense, irrigated land-use amplified and also modified the natural cycle of the near-surface thermal environment.

Dai *et al*. (1999) noted that soil moisture and precipitation can produce a secondary damping effect on DTR. They noted that soil moisture and precipitation together can reduce DTR by 25–50%. It is suggested that soil moisture reduces DTR through evaporative cooling (Dai *et al*., 1999). In other words, cooling of daily maximum temperature leads to a reduction in DTR. Hence, again, we suggest that introduction of irrigation and subsequent artificial increase in root-zone soil moisture enhanced evaporative cooling and reduced growing season mean maximum temperature in Nebraska. Dai *et al*. (1999) suggest that soil moisture is negatively correlated with DTR and, thus, is an important modulator of DTR. Physically, soil moisture limits the rise of maximum temperature by providing moisture for evaporation.

Bonan (1999), in his study on the impacts of land-use change on temperature of the Midwest and the Northeast, noted that the decrease in DTR resulted from greater cooling of daily maximum temperature compared with daily minimum temperature. The present study indicates that, based on coop data, all five irrigated locations record a decreasing trend in growing-season mean maximum temperature. The HCN data set also shows similar results. The analysis based on the coop data set for Boxbutte and Alliance shows a decreasing trend in growing-season mean minimum temperature. On the other hand, York, Osmond, and Oakdale show an increasing trend. The HCN data set for Oakdale and York provide similar results (Table II). Despite two different responses and trends in growing-season mean minimum temperatures, the responses and trends in growing-season mean maximum temperatures in all irrigated locations are clearly showing a decreasing trend. Thus, the decreasing trend in growing-season mean DTR is the result of greater cooling of growing-season mean maximum temperature. This is in agreement with Bonan's (1999) study. It is to be noted that the present study focused primarily on forcings of dry land use and irrigated land use on temperature records. Bonan's (1999) study did not explicitly differentiate between dry and irrigated land uses. His work predominantly looked into croplands of the Midwest and reforestation of the Northeast and their impacts on temperature records. In addition, his study did not include Nebraska and other major irrigated areas of the Great Plains.

In a previous model-based study, Bonan (1997) showed a cooling trend in daily maximum temperatures and decrease in DTR over major agricultural areas of the USA. Our modelling work (Mahmood and Hubbard, 2002) also calculated an up to 36% rise in ET as a result of modification of dry land to irrigated land use. Thus, it is possible to surmise that the decrease in growing-season daytime maxima occurred in response to the high ET and associated evaporative cooling. In short, the forcing of irrigated land use is quite apparent in these cases. However, the signal for dry land is not as consistent as the signal for irrigated locations. We deduce that other forcing factors, e.g. solar variability and large-scale modulation of atmospheric circulation, are also playing a role. Thus, we are dealing with mixed signals for dry land use. Of course, these are present in the irrigated case as well, but they appear to be dominated by the effect of additional ET.

6. Final remarks

This study demonstrates that land-use change has notably modified local and regional growing-season temperature. Major increases in irrigation have resulted in a decrease in mean maximum growing-season temperature. Dry land areas have largely shown an increasing trend in temperature, as is the case with global warming studies. In other words, irrigated land use demonstrated forcing of biophysical factors on near-surface thermal condition through modification of the energy balance. Reduction in DTR is predominantly influenced by depression of mean maximum temperature. It is also found that the decreases of mean maximum, mean, DTR, and extreme maximum temperature are greatest during July and August, when plants' water consumption, ET, and resultant cooling are the greatest. Analysis of dew-point temperature also indicates an increasing trend over the irrigated areas.

The physical reasoning behind the results of this study is in agreement with our previous work and has verified previous findings (Mahmood *et al*., 2001; Mahmood and Hubbard, 2002; Adegoke *et al*., 2003). Model-based estimates from these studies clearly demonstrated a significant increase in soil moisture and latent energy flux under irrigated conditions at both climate and meteorological time scales. These changes in near-surface hydrology were expected to modify the associated thermal condition. The analysis and results of this study confirmed our speculation. We suggest that more research effort should be directed toward land-use change and its impacts on long-term near-surface thermal condition. These studies should combine analysis of recorded data and subsequent modelling studies to explain various mechanisms that have controlled temperature changes. In addition, modelling studies should thoroughly investigate impacts of changes in local and regional thermal condition on local-, regional-, and global-scale atmospheric conditions. Particular emphasis should be given to how these changes interact with projected global change scenarios.

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